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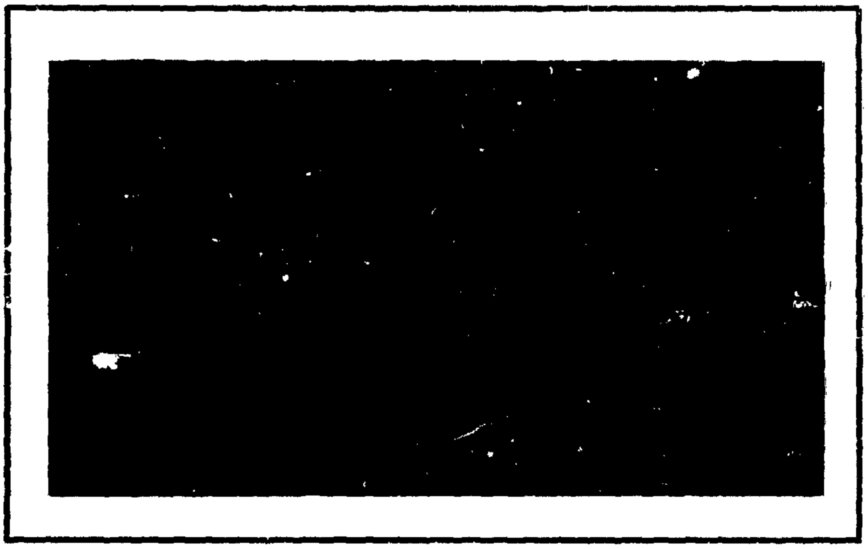

Microwave Laboratory
W. W. Hansen Laboratories of Physics
STANFORD UNIVERSITY
STANFORD, CALIFORNIA

MICROWAVE RESEARCH

Quarterly Status Report No. 16

1 November 1962 - 31 January 1963

Contract Nonr 225(48)

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March 1963

Microwave Laboratory
W. W. Hansen Laboratories of Physics
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Stanford, California

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INTRODUCTION

This report is the Sixteenth Quarterly Status Report under Contract Nonr 225(48), which began on 1 February 1959, and it reports the period of 1 November 1962 through 31 January 1963. At the present time there are seven projects active under this contract:

I. Transverse-wave frequency doublers
II. Parametric refrigeration
III. Nonlinear quantum effects
IV. Optical masers
V. Acoustic wave amplification studies
VI. Ferrite nonlinear propagation
VII. Plasma harmonic generation

Publications

During the period of this quarterly report, 1 November 1962 through 31 January 1963, six papers were prepared for publication, as follows:

G.C. Van Hoven, T. Wessel-Berg, "Negative Energy Fast Waves in Brillouin Flow Beams," Microwave Laboratory Report No. 990, submitted to Appl. Phys. Letters, December 1962.

K.B. Mallory, R.H. Miller, P.A. Szente, "A Simple Grating System for Millimeter and Submillimeter Wavelength Separation," Microwave Laboratory Report No. 995, presented at Millimeter and Submillimeter Wave Conference, Orlando, Florida, January 7-10, 1963, submitted for publication to IRE, Trans. PGMTT.

P.A. Szente, R.H. Miller, K.B. Mallory, "On the Measurement of Detector Impedance," Microwave Laboratory Report No. 996, presented at Millimeter and Submillimeter Wave Conference, Orlando, Florida, January 7-10, 1963, submitted for publication to IRE, Trans. PGMTT.

R.H. Miller, P.A. Szente, K.B. Mallory, "A Measurement of Bolometer Mount Efficiency at Millimeter Wavelengths," Microwave Laboratory Report No. 997, presented at Millimeter and Submillimeter Wave Conference, Orlando, Florida, January 7-10, 1963, submitted for publication to IRE, Trans. PGMTT.

P.A. Szente, R.H. Miller, K.B. Mallory, "Production of Submillimeter Waves by Bunched, Relativistic Electrons," Microwave Laboratory Report No. 998, presented at the Millimeter and Submillimeter Wave Conference, Orlando, Florida, January 7-10, 1963, submitted for publication to IRE, Trans. PGMTT.

R.H. Pantell and R.G. Smith, "Multiple Quantum Effects at Millimeter Wavelengths," Microwave Laboratory Report No. 1001, presented at Millimeter and Submillimeter Wave Conference, Orlando, Florida, January 7-10, 1963, submitted for publication to IRE, Trans. PGMTT.

Certain introductory parts of these projects will be repeated each time so that the reader may more readily follow the work without reference to previous reports.

The Responsible Investigator for this contract is M. Chodorow.

I. TRANSVERSE-WAVE FREQUENCY DOUBLERS

(M. Chodorow, T. Wessel-Berg,* R. E. Hayes)

A. OBJECTIVE

The purpose of this project is to study theoretically and experimentally the utilization of the transverse waves on an electron beam to produce frequency multiplying devices. Such a multiplier would consist of an input coupler, in which one or more of the transverse waves are excited, and an output coupler of the quadrupole type which removes energy from the beam at twice the input frequency. It is expected that relatively high conversion efficiencies may be obtained, and that the realization of multipliers operating at millimeter wavelengths would not pose great difficulties. The present program is to develop the theory of this class of multipliers and build an experimental model having a fundamental frequency in S-band.

B. PRESENT STATUS

The work on this project has been completed and a final report titled "The Theory and Application of Some Transverse-Wave Interactions" will be issued soon. An abstract is given below:

"The results of a theoretical and experimental investigation of transverse-wave couplers and of frequency doublers employing these couplers in conjunction with a resonant quadrupole circuit are described.

"The theoretical description of transverse-wave couplers is based upon the well known coupled mode formalism which describes the interaction between the normal modes existing on a filamentary electron beam in a longitudinal dc magnetic field and the normal modes existing on a periodic circuit. The theory of both traveling-wave and resonant couplers is developed in detail so that the significant characteristics of the coupling interactions are described in terms of known quantities. The coupled mode theory has been extended to include twisted transverse-wave couplers with a resulting clarification of this important class of interaction.

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*Project supervisor.

"The theory shows that the traveling-wave couplers may have a large bandwidth but generally tend to be quite long, due to the low interaction impedance characterizing this type of circuit. Much stronger coupling per unit length is obtained by the use of resonant circuits with a resulting decrease in the required length of the coupler as well as a decrease in the bandwidth. The type of coupler to be used in a particular device depends upon the requirements and restrictions involved.

"The theory of transverse-wave frequency doublers using a resonant quadrupole cavity is developed in detail from a coupled mode approach. It is found that the fast cyclotron wave doubler that has been investigated previously is a special case of a general class of interactions. In general, a periodic quadrupole circuit interacting with any one of the four transverse waves can result in a second harmonic output from the quadrupole if the proper synchronism conditions are met. Some of these cases are of particular interest since they involve an active interaction with the beam that can result in frequency conversion efficiencies that are greater than one hundred per cent.

"Several new types of transverse field coupler and quadrupole circuits are described and typical applications are indicated. The measured interaction impedances and dispersion characteristics show that these circuits can be used in practical devices.

"Finally, an experimental investigation of some transverse wave interactions is described. A tube that allowed the investigation of passive and active frequency doubling as well as amplification in a synchronous-wave klystron was constructed. The experiments were carried out at a frequency of approximately 3.0 kMc and a dc beam power of about 1.0 kw.

"The synchronous wave amplifier, which consisted of two resonant periodic coupler cavities, exhibited a net small signal gain of 8 db and a saturation power output of 40 watts with a dc beam power of approximately 700 watts. The discrepancy of 5 db between the theoretical and experimental gain of the amplifier is attributed to thick beam effects.

"Active frequency doubling involving the interaction between the synchronous waves and a space harmonic component of a quadrupole cavity field was observed although the conversion efficiency was only one per

cent of the theoretical value. This is attributed to thick beam effects that are quite pronounced in quadrupole structures.

"Frequency doubling by means of an interaction between the fast cyclotron wave and a fundamental component of the quadrupole cavity field resulted in a net conversion efficiency of 10 per cent, and a corrected efficiency of about 25 per cent when nonessential coupler losses are accounted for. These results were in complete agreement with the theory. In this case the beam diameter measured in circuit wavelengths was very small so that the deleterious thick beam effects were not expected."

II. PARAMETRIC REFRIGERATION

(P. A. Sturrock,* A. Karp, G. C. Van Hoven)

A. OBJECTIVE

The aim of this program is to conduct an investigation and experimental verification of a parametric mechanism for the removal of negative energy noise from an electron stream.[1] If the noise can be removed as predicted, then the "refrigerated" beam can be used to provide normal traveling-wave amplification with arbitrarily low noise figure.

B. PRESENT STATUS

This past quarter has been devoted to the preparation of a final report on the experimental work of this program. The abstract of this report follows:

"This report presents an experimental demonstration of two heretofore unobserved nonlinear effects in systems supporting space-charge waves. The discussion is based on a second order physical theory which exhibits nonlinear coupling of these waves to those supported by an external circuit. The most important prediction of this theory is the possibility, which has been verified, of removing negative energy kinetic excitation from the slow space-charge wave.

"The physical theory, a perturbation analysis in displacement variables, describes all possible second order nonlinear interactions. A small signal power theorem, applicable to three frequency excitation, is derived from the dynamical equations. The conditions, central to the concept of this paper, under which this simplification is justified, are discussed.

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*Project supervisor

[1] P. A. Sturrock, "Parametric Refrigeration--a Mechanism for the Removal of Noise from the Slow Wave of an Electron Beam," Microwave Laboratory Report No. 656, Stanford University (October 1959).

"The model is further specialized to the empirically valid case of a two-mode circuit to stream wave interaction. A quasi-linear coupled mode analysis is then developed which takes account of the kinematics of multiple frequency, multiple mode, propagation. A general criterion for predicting the result of an arbitrary parametric coupling is given.

"An experimental coupler, designed to test these principles, is described. The character of the interactions and their placement on the dispersion diagram are shown to agree with the predictions. Parametric reverse wave amplification and, at higher coupling levels, spontaneous oscillation have been observed. Means were inserted which allowed the excitation of space-charge waves at the cathode. A demonstration of parametric refrigeration, the transferral of negative energy excitation from the stream to the circuit, is described.

"The low noise amplification possibilities of devices using these principles and several problems connected with the pumping modulation are discussed. Finally, a number of alternative configurations are proposed, including a new class of fast wave amplifiers."

III. NONLINEAR QUANTUM EFFECTS

(P. D. Coleman,* R. H. Pantell, R. G. Smith, T. H. Savits)

A. OBJECTIVE

It is the purpose of this work to investigate theoretically and experimentally nonlinear quantum effects, including the possibility of harmonic generation by the use of multiple quantum transitions. In a device using this principle, a quantum system with a pair of discrete energy levels whose spacing corresponds to the frequency region of interest is subjected to an electromagnetic field at a frequency which is some subharmonic of the natural transition. If the interaction between the field and the system is of sufficient strength, then the power will be generated at the normal transition frequency. The present objective of this study is to determine under what conditions a strong interaction may be expected to occur. Another aspect to be studied is that of parametric amplification using these principles.

*Project supervisor

B. PRESENT STATUS

A technical report on this project has been written; the abstract from this report follows:

"The research described in this report is concerned with a study of multiple quantum effects occurring in the interaction of radiation with matter. These effects involve the interaction of more than a single quantum of radiation with an atom or molecule and are found to have a nonlinear character. Previous work on the subject was principally concerned with the appearance of these effects in microwave and radio frequency absorption spectra. In this research a more detailed study is made of the problem with an emphasis on possible applications.

"An analytical approach to the problem is presented in which the macroscopic linear and nonlinear properties of a medium are related to the microscopic properties of the atoms constituting the medium. These microscopic properties are in turn derived from a quantum mechanical formulation using the density matrix approach. By using this formalism, the nonlinear characteristics, coming as a result of the multiple quantum transitions, may be evaluated in terms of the linear properties, which are in turn measurable by spectroscopic means.

"Detailed analyses of three specific cases are presented: (1) Third harmonic generation in a two-level electric dipole system; (2) Parametric effects in a two-level electric dipole system; (3) Second harmonic generation in a three-level system.

1. "A two-level electric dipole system is found to present a third-order nonlinearity with a term in the polarization proportional to the cube of the applied field. When the applied field varies sinusoidally in time, this results in a component varying at the third harmonic of the applied frequency. The nonlinear term is most strong when either the applied frequency or the third harmonic is near the natural transition frequency. A dynamic shift of the natural frequency due to the strong applied radiation fields is predicted from the theory and is seen to be important when a transition with a narrow linewidth is employed. The third harmonic power is calculated, assuming a resonant cavity, and the dependence on

the parameters of the cavity and quantum system is discussed. Saturation effects are found to limit the high power behavior.

2. "The same two-level electric dipole system is also studied as a parametric amplifier where now the atomic resonance plays the part of the idler circuit. The condition on the frequencies of the pump and signal frequencies is found to be $2\omega_p = \omega_s + \Omega$, where ω_p and ω_s are the pump and signal frequencies, respectively. Conditions for parametric oscillation are calculated in terms of the parameters of the cavity and molecule.

3. "A three-level system is considered as a second harmonic generator. The magnitude of the nonlinearity is found to be dependent on the position of the center level being maximum when one linewidth from the midpoint of the outer levels. The output power is calculated and the dependence on concentration and other parameters of the system is considered.

"Two experiments in which these phenomena are observed are described. Third harmonic generation, using the inversion transition in ammonia, was used in the first experiment. The second experiment utilized second harmonic generation in ruby."

IV. OPTICAL MASERS

(A. L. Schawlow,* H. W. Moos, G. F. Imbusch, L. Mollenauer)

A. OBJECTIVE

The purpose of this work is to improve and extend the performance of optical masers, so that they can be used for physical research problems. It is desired to make optical masers approach more nearly the ideal characteristics of extreme monochromaticity, high power and directionality. It is also desired to have optical masers operating at a wide range of wavelengths. Wherever the characteristics of available optical masers are adequate, it is intended to apply them to appropriate problems in physics, and to the realization of new kinds of instruments.

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*Project supervisor

B. PRESENT STATUS

1. Monochromatic Ruby Optical Maser

The experimental work reported previously has not been continued. Some time has been spent in deepening our theoretical understanding of the system and in preparing a complete report which will be presented by A. L. Schawlow at the Polytechnic Institute of Brooklyn Symposium on Optical Masers, April 16-18, 1963.

2. Multiple-Beam Interferometry with Large Plate Separation

We have extended the tilted plate interferometer described in the previous reports to a separation of 60 cm. This is a large separation for any type of multiple beam interferometry.

That Fabry-Perot interferometric studies of lasers are not always satisfactory, because of the special nature of a laser output, seems to be the experience of our own and other laboratories. Not only does the highly collimated light produce few rings, but the spatial coherence produces spurious effects such as ghosts when the system is out of focus. We have found that, if one randomizes the spatial coherence by such a simple method as introducing a ground glass screen into the beam, excellent results are obtained with no spurious effects. Moving the screen to average, the grain produces excellent results of a "textbook quality." The results of this section will be reported by H. W. Moos and G. F. Imbusch at the Optical Society of America Meeting, March 25-27, 1963.

V. ACOUSTIC WAVE AMPLIFICATION STUDIES

(C. F. Quate)

A. OBJECTIVE

The project is devoted to the studies of the microwave region of acoustic wave amplification in piezoelectric semiconductors. The first experiments on this process were reported by Hutson, McFee and White[1]

[1] A. R. Hutson, J. H. McFee, D. L. White, "Ultrasonic Amplification in Cds," Phys. Rev. Letters 7, 237 (September 1961).

wherein they demonstrated that electrons drifting through Cadmium Sulphide could give up energy to the acoustic waves if the electrons were drifting faster than the velocity of sound. They measured gains of 45 db/cm at 45 Mc. We have analyzed this process of amplification via coupled mode theory.[2] Both the drifting carriers and the elastic media can support propagating waves which are coupled by the electric fields in the piezoelectric crystals. When the carriers drift with an average velocity slightly lower than the velocity of sound, they absorb energy from the acoustic waves, and when their drift velocity exceeds the velocity of sound, they give up energy to the elastic waves. It is an important principle which demonstrates strong cumulative interaction between traveling waves and the conduction electrons. The simple theory of the process would indicate that the amplification process should be valid well into the microwave range. It is our objective to investigate the nature of the amplifying process at these higher frequencies.

B. PRESENT STATUS

During the past few months we have been successful in fabricating samples as illustrated in Fig. 1. These consist of a CdS wafer sandwich between two quartz transducers. This design is similar to those discussed in previous reports. The bounds between quartz and CdS are now made of indium and they are mechanically rugged and able to withstand cycling to low temperatures. At room temperature they have small loss at 600 Mc. With these samples we have studied the acoustic gain in the range of 500 - 700 Mc.

The transmitted pulse in the longitudinal mode through an insulating CdS crystal is shown in Fig. 2. The small pulse to the left is the transmitter leakage, and the pulse to the right is the reflected wave from the bonds - it is at least 20 db down from the incident signal. This indicates that near 600 Mc the bonds from quartz to CdS do not represent an acoustic mismatch for longitudinal waves. At lower frequencies, 475 Mc, the reflected pulse is only about 10 db down from the incident

[2] C. F. Quate, "Coupled Mode Theory of Acoustic Wave Amplifiers," Microwave Laboratory Report No. 889, Stanford University (February 1962).

pulse. We have no data as yet for higher frequencies, and we do not fully appreciate why the reflection is a function of frequency.

When we applied a drift field across the pulse we obtained a V-I characteristic as shown in Fig. 3. The lower trace indicates that the crystal is ohmic, whereas the upper trace shows the non-ohmic behavior with the current saturating in the manner first discussed by R. Smith.[3] We find, as do others,[4] that there is rf oscillation during this interval which we attribute to shear waves.

The spectrum of noise has been investigated in the range of 100-1000 Mc. Typical characteristics are illustrated in Figs. 4, 5, and 6. We see that the spectrum is strongly peaked in the range of 100 - 400 Mc. We found a small peak in output near 430 Mc but nothing above that frequency. The spectrum of oscillations is of importance for if one could find a way of controlling this spectrum and limiting it to one frequency, we can see in Fig. 3 that considerable power is converted to this mode.

The gain through the crystal is illustrated in Figs. 7 and 8.

In Fig. 7 we show the acoustic pulse in the absence of a drift field at 500 Mc. In Fig. 8 we show the pulse in the presence of a drift field. It illustrates some 23 db change in amplitude with and without the drift field.

This represents the present status of the work. It should be noted that the voltage we are displaying is measured at the indium contacts of the crystal. It is not clear that this represents the field across the crystal, and we are investigating possible ways of checking this. The high field at which we get gain (greater than 6000 V/cm) and the fact that we are unable to increase the field past the point of maximum gain would lead one to suspect nonuniform field within the crystal.

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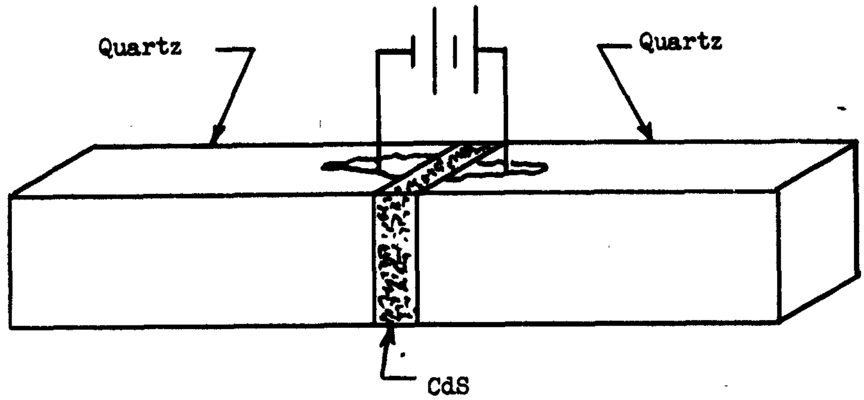
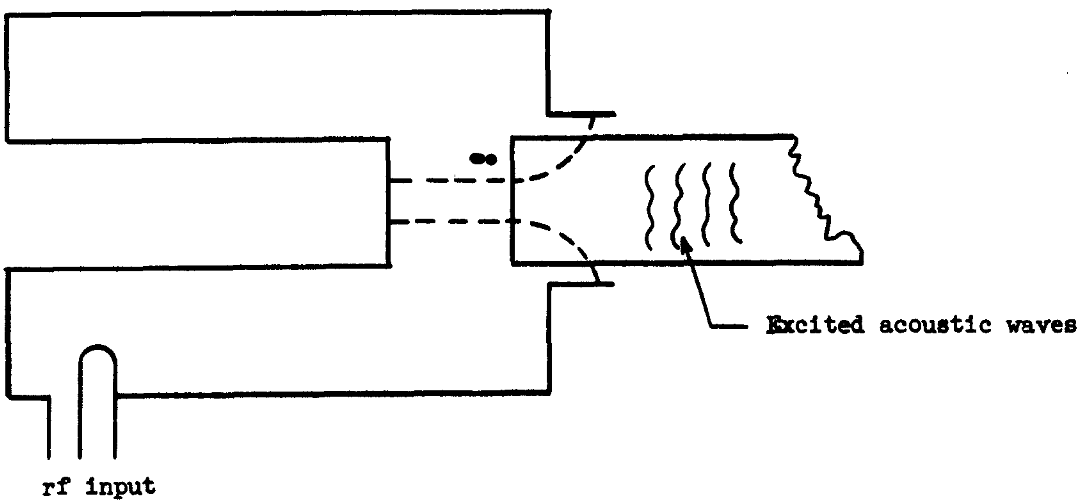
[3] R. W. Smith, Phys. Rev. Ltrs. 9, 87 (1962).

[4] J. W. McFee, Bell Telephone Labs., Inc., private communication.



(a) Crystal sandwich.



(b) Excitation through quartz.

FIG. 1--Typical sandwich used to study acoustic amplification and oscillation.
Length of CdS crystal = 1.08 mm
Area of CdS crystal = 35 mm^2.

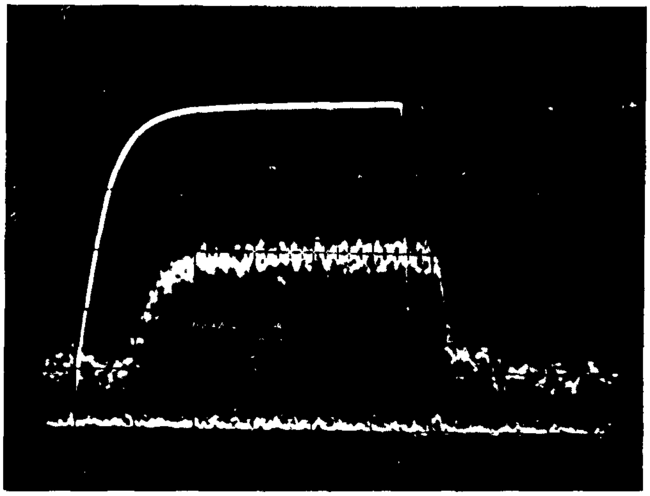


FIG. 2--Transmitted acoustic pulse at 600 Mc. Horizon scale is 5 μsec/cm. Vertical scale is proportional to amplitude. Pulse to the left is the transmitter leakage pulse. Pulse to the right is the acoustic pulse, and it is at least 20 db below incident pulse.

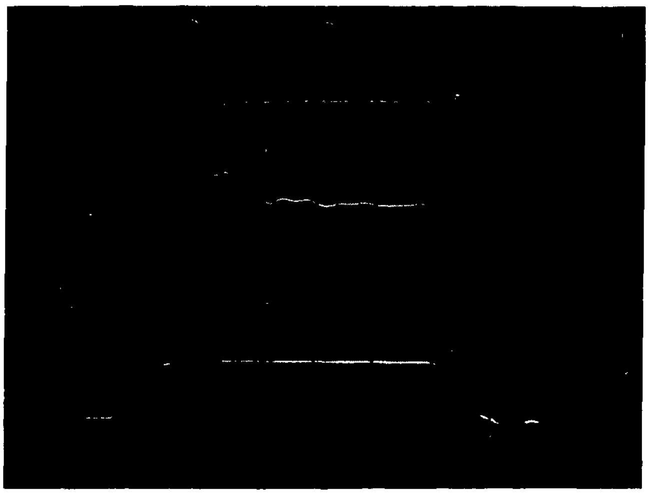


FIG. 3--V-I characteristic for CdS wafer for two different light levels. Smooth trace is the voltage applied to crystal contacts. Rippled curve is current through crystal. No significance is attached to rippling, for it is a product of the measuring circuit. Horizontal scale 2 μs/cm. Vertical scale for voltage = 100 v/cm. Vertical scale for current = 80 ma/cm. Crystal area = 35 mm^2. Crystal length = 1.08 mm.

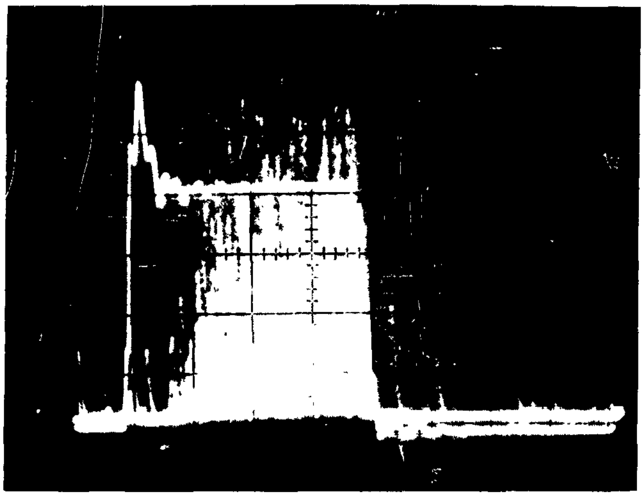


FIG. 4--Illustration of noise within a 2 Mc band at 156 Mc. Included for reference is the current through the crystal (vertical scale = 100 ma/cm), (horizontal scale = 5 μs/cm). Note build-up of oscillation as current decreases. Noise is measured by monitoring current in the crystal leads.

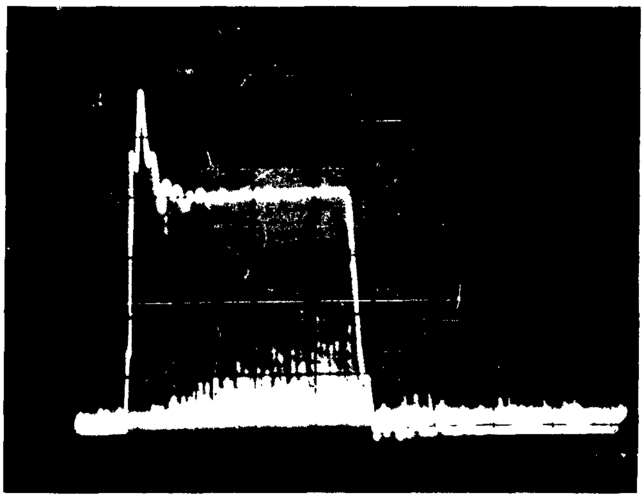


FIG. 5--Similar to FIG. 4 at 179 Mc.

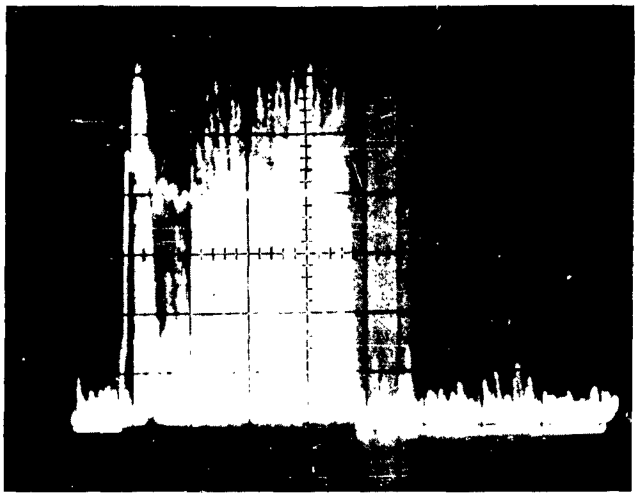


FIG. 6--Similar to FIG. 4 at 182 Mc.

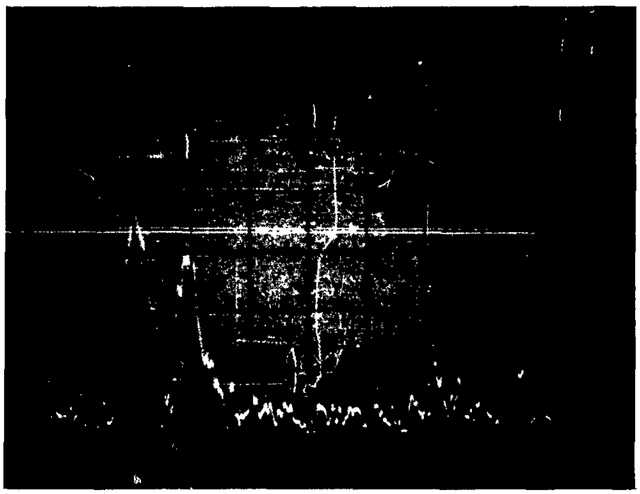


FIG. 7--Reference plots to show transmission if acoustic pulse in absence of drift field. Frequency = 500 Mc. Horizontal scale 5 μs/cm. First pulse is leakage from transmitter.

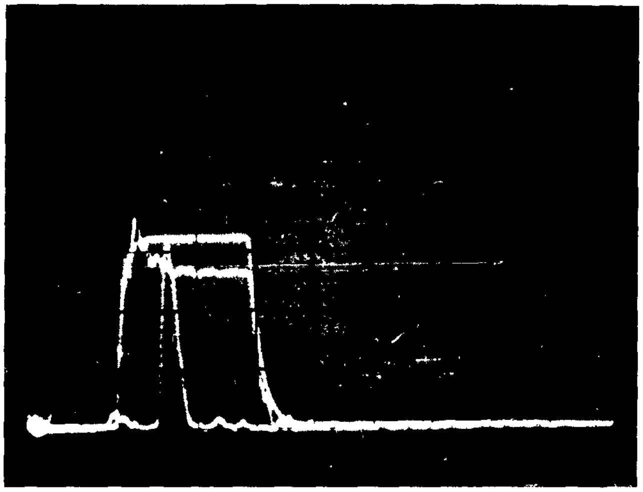


FIG. 8--Illustration of gain with applied drift field. Smooth trace is voltage across crystal (scale 200 volts/cm). Rippled trace is current through crystal (scale 100 ma/cm). Signal has been attenuated by 23 db over that in FIG. 7, and we can see this by the relative amplitude of the transmitter pulse. Thus the signal has increased by 23 db (or 21 db/mm) in the presence of drift field. Note that the signal pulse appears delayed by 2.6 μsec in this display since it traveled through 1 cm of quartz between the CdS wafer and the transducer. Thus the peak gain as illustrated occurs at the peak in the current trace. If the signal pulse is delayed to the point where it traverses the crystal during the time that it is oscillating the gain decreases from 23 db to 10 db.

VI. FERRITE NONLINEAR PROPAGATION

(B. Auld,* D. K. Winslow, M. Omori)

A. OBJECTIVE

The objective of this project is to investigate nonlinear microwave propagation in gyromagnetic media. Up to the present time the principal emphasis has been on the study of frequency doubling in propagating circuits. Other topics to be investigated include mixing, shock-wave formation, parametric amplification, electromagnetic instabilities analogous to Suhl spin wave instabilities, and jump phenomena in propagating systems.

B. PRESENT STATUS

A review and refinement of the theory of susceptibility of the uniform mode when subjected to degenerate parallel pumping has been carried out during this quarter. The results predicted are not in agreement with those of Morgenthaler.[1]

The analysis was carried out by two different methods:

a) by using the equations of motion with a Gilbert damping term,

$$\dot{m} = \gamma(\vec{M} \times \vec{H}_{int}) - \frac{\alpha}{|M|} (\vec{M} \times \dot{\vec{M}}) \quad , \qquad (1)$$

b) by using the transformation method,[2] with the resonant frequency assumed complex,

$$\dot{b} = i(\omega_r + i\eta)b \quad .$$

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*Project supervisor

[1] F. R. Morgenthaler, "Survey of Ferromagnetic Resonance in Small Ferrimagnetic Ellipsoids," J. Appl. Phys. 31S, 95S-97S (May 1960).

[2] E. Schlömann, "Ferromagnetic Resonance at High Power Levels," Raytheon Technical Report No. R-48 (October 1, 1959).

Comparison of the two results with no pumping shows that they are the same when η is replaced by

$$\eta = \frac{\gamma(\omega_r + i\eta)}{2\omega_r} \frac{\alpha\omega}{\gamma} = \frac{\partial\omega}{\partial H} \frac{\alpha\omega}{\gamma} .$$

For simplicity the following presentation of the theory, therefore, will be given in terms of the transformation method.

With a parallel pump field in the z-direction included and higher order terms neglected, the transformed equations of motion in b-space are

$$\dot{b} = i\left\{(\omega_r + i\eta)b - 2A\cos(2\omega t + \phi) \cdot b^* + 2B\cos(2\omega t + \phi) \cdot b - 2F\cos\omega t\right\} , \tag{2}$$

where

$$A = \frac{\omega_c}{\omega_r}\frac{\omega_{/\!/}}{2} \qquad N = \frac{N_x + N_y}{2}$$

$$B = \frac{\omega_M N'}{\omega_r}\frac{\omega_{/\!/}}{2} \qquad N' = \frac{N_x^2 - N_y}{2}$$

$$F = (\lambda - \mu)\frac{\omega_\perp}{2} \qquad \lambda = \sqrt{\frac{\omega_c + \omega_r}{2\omega_r}}$$

$$\omega_c = \gamma H_0 + \gamma 4\pi M(N - N_z) \qquad \mu = \sqrt{\frac{\omega_c - \omega_r}{2\omega_r}}$$

$$\omega_r = \sqrt{\omega_x \omega_y} = \sqrt{\left\{\gamma H_0 + \gamma 4\pi M(N_x - N_z)\right\}\left\{\gamma H_0 + \gamma 4\pi M(N_y - N_z)\right\}} ,$$

$$\omega_{/\!/} = \gamma h_{/\!/}$$

$$\omega_\perp = \gamma h_x$$

and a linear driving field h_x is assumed. For an assumed steady state solution,

$$b = \bar{b}e^{i\omega t} = (b' + ib'')e^{i\omega t} ,$$

the real and imaginary parts of the susceptibility are

$$\chi' = \frac{b'}{\lambda + \mu} \frac{M_s}{h_x}$$

$$\chi'' = \frac{b''}{\lambda + \mu} \frac{M_s}{h_x} .$$

If the off-resonance term in Eq. (2) is neglected, the pumped steady-state susceptibility is

$$\chi' = \frac{\omega_r - \omega - A \cos \phi}{(\omega_r - \omega)^2 + \eta^2 - A^2} \sqrt{\frac{\omega_y}{\omega_x}} \frac{\gamma M_s}{2}$$

$$\chi'' = - \frac{\eta - A \cos \phi}{(\omega_r - \omega)^2 + \eta^2 - A^2} \sqrt{\frac{\omega_y}{\omega_x}} \frac{\gamma M_s}{2} . \qquad (3)$$

By comparison, the results obtained from Eq. (1) are

$$\frac{\chi_{xx}}{\gamma M_s} = \frac{(\omega_r^2 - \omega^2)\omega_y + \omega_{\parallel}/2(\omega_y^2 - \omega^2) \cos \phi}{(\omega_r^2 - \omega^2)^2 + (\alpha\omega)^2(\omega_x + \omega_y)^2 - \omega_{\parallel}^2/4(\omega_x^2 + \omega_y^2 - 2\omega^2)}$$

$$- i \frac{\alpha\omega(\omega_r^2 - \omega^2) - \alpha\omega(\omega_x + \omega_y)\omega_y - \omega_{\parallel}/2(\omega_y^2 - \omega^2) \sin \phi}{(\omega_r^2 - \omega^2)^2 + (\alpha\omega)^2(\omega_x + \omega_y)^2 - \omega_{\parallel}^2/4(\omega_x^2 + \omega_y^2 - 2\omega^2)} ,$$

where the higher order terms in $\alpha\omega$ are neglected. This result reduces

to the expression which was obtained by I. Bady[3] for the unpumped case.

Characteristics of the Pumped Susceptibility

1. Imaginary part

The imaginary part of the pumped susceptibility becomes maximum at $\omega_r = \omega$, and it has the value

$$\sqrt{\frac{\omega_x}{\omega_y}} \frac{2}{\gamma M_s} \chi''_{res} = - \frac{\eta - A \sin \phi}{\eta^2 - A^2} = - \frac{1}{\eta} \frac{1 - (h_{/\!/}/h_{crit}) \sin \phi}{1 - (h_{/\!/}/h_{crit})^2} ,$$

where

$$h_{crit} = \frac{\Delta H_0}{N_y - N_x} \frac{\omega_x + \omega_y}{\omega_H} .$$

A somewhat similar expression has also been obtained by M. Sparks[4] of this laboratory. If the linewidth is defined, as is the conventional way, as the difference in field between points $\chi'' = \chi''_{res}/2$, the linewidth is

$$\Delta H = \frac{\partial H}{\partial \omega_r} \Delta \omega_r = 2 \frac{\partial H}{\partial \omega_r} \sqrt{\eta^2 - A^2} ,$$

which is independent of the phase angle between signal and pump. The dependence of χ'' on ω_r for different values of ϕ is shown in Fig. 1.

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[3] I. Bady, "Ferrites with Planar Anisotropy at Microwave Frequencies," IRE, Trans. PGMTT, MTT-9, 52-62 (January 1961).

[4] M. Sparks, Private letter to D. K. Winslow (October 2, 1961).

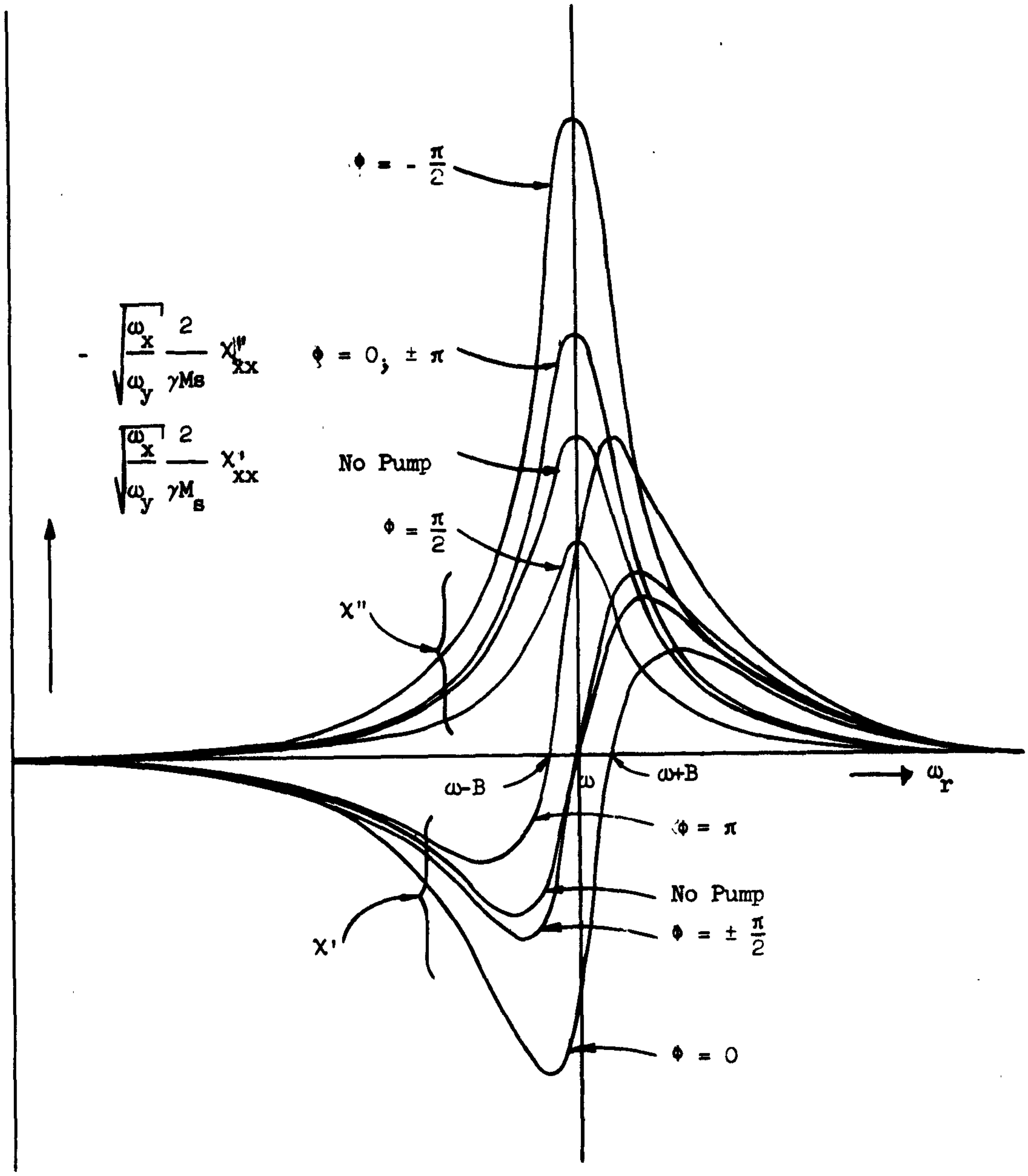

FIG. 1—Susceptibility curves for $\frac{\eta}{B} = 2$ or $\frac{h_{/\!/}}{h_{crit}} = \frac{1}{2}$.

2. **Real Part**

The real part of pumped susceptibility becomes zero at[5]

$$\omega_r = \omega - A \cos \phi \tag{4}$$

and becomes maximum at

$$\omega_r = \omega + A \cos \phi \pm \sqrt{\eta^2 - A^2 \sin^2 \phi} \ .$$

The maximum values of the real part of the pumped susceptibility are then,

$$\chi''_{max} = \frac{\pm \sqrt{\eta^2 - A^2 \sin^2 \phi}}{2\eta^2 - A^2(1 - \cos \phi) \pm 2A \sqrt{\eta^2 - A^2 \sin^2 \phi} \cos \phi} \sqrt{\frac{\omega_y}{\omega_x}} \frac{\gamma M_s}{2} ,$$

which are unequal, except when $\phi = \pm \pi/2$ (Fig. 1).

3. Absolute Value

In an actual measurement of an absorption curve the magnitude of the susceptibility is observed;[6] and, in general, the linewidth of a sample is determined by the condition $|\chi| = |\chi|_{max}/\sqrt{2}$. In the unpumped case the linewidth obtained from the $\chi''_{res}/2$ criterion is the same as from the $|\chi|_{max}/\sqrt{2}$ criterion. In Fig. 2a the dependence of $|\chi|$ on ω_r is shown for different values of ϕ . This indicates:

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[5] An interesting point here is that when ω_r has the value given in Eq. (4), the imaginary part of the pumped susceptibility becomes

$$\chi''(\chi' = 0) = - 1/(\eta + A \sin \phi)\sqrt{\omega_y/\omega_x}(\gamma M_s)/2 \ .$$

If the pumped linewidth is defined, in general, to be $\Delta H_{eff} = M_s/\chi''(\chi' = 0)$, which is correct for the unpumped case, ΔH_{eff} becomes

$$\Delta H_{eff} = - 2/\gamma\sqrt{\omega_x/\omega_y} (\eta + A \sin \phi) \ . \tag{5}$$

This result is identical with that of Morgenthaler, except for a factor of -2 in the second term on the right hand side.

[6] L.K. Anderson, "Ferromagnetic Relaxation Measurements and Microwave Circuit Properties of Ferrite Ellipsoids," Microwave Laboratory Report No. 880, Stanford University (February 1962).

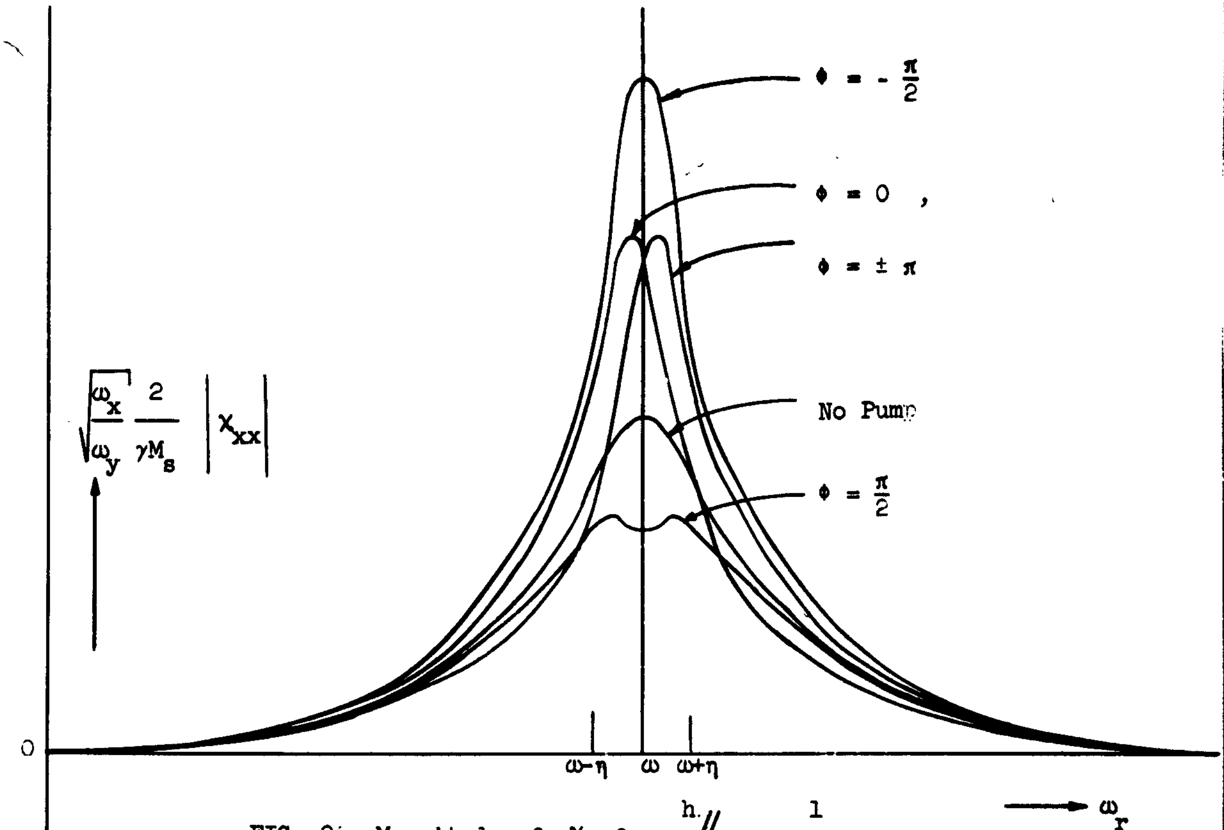

FIG. 2a--Magnitude of χ for $\frac{h_{/\!/}}{h_{crit}} = \frac{1}{2}$.

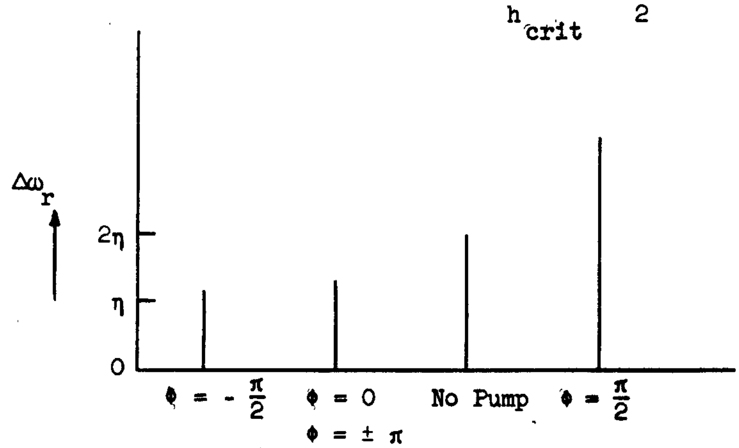

FIG. 2b-- Effective linewidth for $\frac{h_{/\!/}}{h_{crit}} = \frac{1}{2}$.

a) a shift of resonant field (the field to give maximum $|\chi|$) ,

$$\delta H = \frac{\partial H}{\partial \omega_r} \partial \omega_r \lesssim \frac{\omega_r}{\omega_x + \omega_y} \frac{\omega_0}{\omega_r} h_{//} ,$$

b) the presence of double peaks in the region near $\phi = \pi/2$,

c) a pumping effect and shift of resonance field at $\phi = 0$ and $\pm \pi/2$. There is no pumping effect at these phase angles according to the result by Morgenthaler.[1]

The effective, or apparent linewidths, obtained graphically from Fig. 2a, are plotted in Fig. 2b. These results also show that Eq. (5) may not apply for the case.

In the above derivation, no radiation damping has been considered. In the next quarter the analyses will be extended to include this effect. A normal mode approach[7,8] will then be used in developing a theory of degenerate parallel pumping of magnetostatic modes in general.

VII. PLASMA HARMONIC GENERATION

(G. S. Kino,* J. H. Krenz)

A. OBJECTIVE

This project is one in which we hope to generate millimeter-wave harmonics of a high-power fundamental at microwave frequencies by making use of the nonlinear properties of a gas discharge plasma. The objective for this project is twofold: (1) to understand the mechanism controlling harmonic generation in a plasma, and (2) to obtain appreciable rf power

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[7] E. Schlömann, R.I. Joseph, "Instability of Spin Waves and Magnetostatic Modes in a Microwave Magnetic Field Applied Parallel to the dc Field," J. Appl. Phys. 32, 1006-1004 (June 1961).

[8] R.T. Denton, "Theoretical and Experimental Characteristics of a Ferromagnetic Amplifier Using Longitudinal Pumping," J. Appl. Phys. 31S, 300S-307S (March 1961).

*Project supervisor

at millimeter wavelengths by means of harmonic generation in a nonlinear plasma medium.

B. PRESENT STATUS

The effort during the last quarter has been directed toward understanding the electrodeless or spherical discharge reported previously. This configuration is interesting due to its high efficiency as a harmonic generator.

While high efficiencies have been reported, they were based upon the net power absorbed by the plasma. The nature of the plasma, however, required a high mismatch in order to maintain the plasma. This required a high reflected power, which for the purposes of a device was wasted. The net efficiency for the second harmonic was therefore considerably lower than the 25% plasma efficiency. Experimentally, we have attempted to improve the match by providing a second rf field in the UHF range to maintain the plasma. With a power of only a few hundred milliwatts, the stability of the plasma has been found to be greatly improved. The input VSWR may now be readily held to less than 2.0 while maintaining an output efficiency of 20%. A mercury plasma in a sealed-off bulb was utilized due to its ease of operation.

While the output of the plasma generator has been assumed to be coherent, this has never been verified due to the difficulties associated with maintaining a stable plasma. Most of the experiments have used a high power magnetron which in itself is very noisy with a relatively wide spectrum. A signal generator, traveling-wave tube amplifier, and a klystron were assembled so as to produce up to 20 watts cw. Utilizing this as a driver for the plasma, the output, as observed on the Polaroid spectrum analyzer, had no detectable side bands. This indicates that the effects of collisions or other random processes which could destroy the coherence of the output are negligible.

Experimentally, it has also been observed that the output is very critically dependent upon the input power which is suggestive of a resonant condition involving the plasma density. Increasing the input power beyond that required for maximum output not only exhibits a saturation, but also a marked decrease in output. This is particularly evident with the second

harmonic since the power absorbed by the plasma is very dependent upon the output. A bulb with two probes was constructed so that the plasma density could be measured. Unfortunately, the larger geometry of this device reduced the harmonic efficiency. It was found, however, that at the point of maximum efficiency, the plasma density was such as to correspond to the dipole resonance of a spherical plasma $(\omega_p/\omega = \sqrt{3})$ at the second harmonic. This has been further substantiated by performing a series of low frequency experiments with an input frequency of 750 Mc/s. Detailed measurements of the third through seventh harmonics indicate a resonance with input power for each harmonic. The input power for each harmonic increased with harmonic number. An interesting aspect of the harmonics was that the maximum output for the various harmonics remained nearly constant (within a factor of 2). The efficiency did drop but only because of the increase in input power. Even for the seventh harmonic, an efficiency of 1.0% was obtained. While the cw powers necessary to obtain harmonics above the third for S-band result in dissipation problems, pulse measurements indicate that the same resonant phenomena take place. The plasma density appears to stabilize after approximately 10 μsec. It is necessary, however, to maintain a low density plasma in between pulses by an external source since the power levels involved are not sufficient to initiate breakdown.

A theory has been developed in which a resonant condition is assumed. Since at this condition the electric field is nearly uniform,[1] spatial variations of number density give rise to the harmonic generation by utilizing the radial dependence of plasma density as derived by Tonks and Langmuir[2] and the numerical data of Harrison,[3] the harmonics have been calculated. Our initial results indicate very good agreement for the second harmonic. Higher harmonics, however, depend strongly upon the boundary since higher order spatial derivatives of the density are needed. The

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[1] F. W. Crawford, G. S. Kino, Microwave Laboratory Report No. 974, Stanford University (October 1962).

[2] L. Tonks, I. Langmuir, Phys. Rev. 34, 876 (September 1929).

[3] E. R. Harrison, J. Electr. and Contr. 5, 319 (October 1958).

transition region between the plasma and the sheath appears to be very significant and is such that neither the sheath theory nor the plasma theory is sufficient by itself.

If spatial variations in number density exist, an rf charge density at the fundamental frequency is obtained.[4] This, in effect, is a variation of the plasma reactance. If the impedance at half the drive frequency is sufficiently high, i.e., if there is a resonance of the plasma, parametric oscillations should occur with sufficiently large pump power. The harmonic generation device has been modified so as to look for parametric oscillations. Oscillations with an output of a few milliwatts have been observed with an input power of approximately 0.6 watts. The low input power is necessary in order to produce a resonance at half of the input frequency of 2.85 kMc. While detailed measurements are yet to be performed, the presence of oscillations does substantiate that a strong nonlinear reactive mechanism is present and does tend to indicate that our hypothesis of a plasma resonance is correct. The high harmonic efficiency also suggests the presence of such a mechanism, so that finding these parametric oscillations is not surprising. Detailed measurements of the output as a function of input should also yield additional information of the postulated resonance phenomena. This work will be carried out during the next quarter.

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[4] J. H. Krenz, G. S. Kino, Microwave Laboratory Report No. 948, Stanford University (September 1962).

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